32. THE SUSCEPTIBILITY AND TIME-DEPENDENT MAGNETIZATION OF BASALTS FROM DEEP SEA DRILLING PROJECT HOLE 534A, BLAKE PLATEAU[1]

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ABSTRACT

Basalts from Hole 534A are among the oldest recovered from the ocean bottom, dating from the opening of the Atlantic 155 Ma. Upon exposure to a 1-Oe field for one week, these basalts acquire a viscous remanent magnetization (VRM), which ranges from 4 to 223% of their natural remanent magnetization (NRM). A magnetic field of similar magnitude is observed in the paleomagnetic lab of the *Glomar Challenger*, and it is therefore doubtful if accurate measurements of magnetic moment in such rocks can be made on board unless the paleomagnetic area is magnetically shielded. No correlation is observed between the Konigsberger ratio (Q), which is usually less than 3, and the ability to acquire a VRM. The VRM shows both a log t dependence and a Richter aftereffect. Both of these, but especially the log t dependence, will cause the susceptibility measurements (made by applying a magnetic field for a very short time) to be minimum values. The susceptibility and derived Q should therefore be used cautiously for magnetic anomaly interpretation, because they can cause the importance of the induced magnetization to be underestimated.

INTRODUCTION

Oceanic basalts are well known for their ability to readily acquire a viscous remanent magnetization (VRM) upon exposure to weak magnetic fields (e.g., Lowrie and Kent, 1978). A high viscosity could cause laboratory measurements of susceptibility to be too low and could lead to an underestimation of the induced magnetization, which in most seafloor magnetic anomaly interpretations is assumed to be negligible. The basalts recovered from the basement of Hole 534A were studied in this regard, and preliminary results are presented herein.

NATURAL REMANENT MAGNETIZATION AND SUSCEPTIBILITY

Eighteen meters of basalt were recovered on the Leg 76 extension, which completed drilling Hole 534A to a depth of 27 m into basement. These basalts, among the oldest ever recovered from the ocean, are dated from the opening of the Atlantic Ocean 155 Ma. Fifty-one samples were collected by shipboard paleomagnetists, and measurements of natural remanent magnetization (NRM) and initial susceptibility ($\varkappa$) were made on board the *Glomar Challenger*. NRM measurements were made with a Digico magnetometer located in the paleomagnetic van in the hull of the ship. Long-term monitoring of the magnetic field in this area indicated that a horizontal field of approximately 0.9 Oe was parallel to the length of the ship and that its strength and direction varied only slightly ($\sim 10\%$) with the orientation of the ship. Because a field of such strength and consistency has the potential to induce a significant viscous component, the NRM measurements may have been influenced by the ambient field.

[1] Sheridan, R. E., Gradstein, F. M., et al., *Init. Repts. DSDP*, 76: Washington (U.S. Govt. Printing Office).

Susceptibility measurements were made on long cores and discrete samples with the shipboard Bison Model 3101 Susceptibility Bridge. Long-core susceptibility was measured on all basalt cores in their liners before the cores were split into archive and working halves. Because a calibration constant was not available for the long-core measurements, these values are only significant relative to each other. In addition, absolute susceptibility values were obtained from the 51 1-in. cylinders minicored from the working half. Figure 1 displays the results of these measurements.

The relative susceptibility of the long cores shows rather consistent values, with two exceptions. The low trend in Section 2 of Core 129 is probably due to the unusual lithology at that depth: brecciated and highly fractured basalt intruded by hydrothermal quartz, calcite, and altered sediments. This rock type should have less ferromagnetic material than a pure basalt and therefore a lower susceptibility. The cause of the sharp spike in Section 3 of Core 130 is not known, as it cannot be explained by visual observations. Other minor variations in the long-core relative susceptibility are most likely due to variations in abundance of fractures and slight variations in the magnetic grain size.

We had hoped to calibrate the long-core susceptibilities by using the measured susceptibilities of discrete samples. However, the correspondence between the two plots is not good. For example, there are discrete samples with low susceptibilities (~ 1 G/Oe) where no low trends are recorded in the long-core measurements. This implies that there are small-scale variations that are not apparent in long-core values because of an averaging effect. The most reasonable calibration is to associate a value between 2.7 and 3.1 $\times 10^{-3}$ G/Oe (average and median values of discrete samples) with the main trend in the long-core plot.

Eleven of the 51 minicores were taken to the paleomagnetic laboratory of the University of Texas for further studies. Seven additional samples were cut in half,

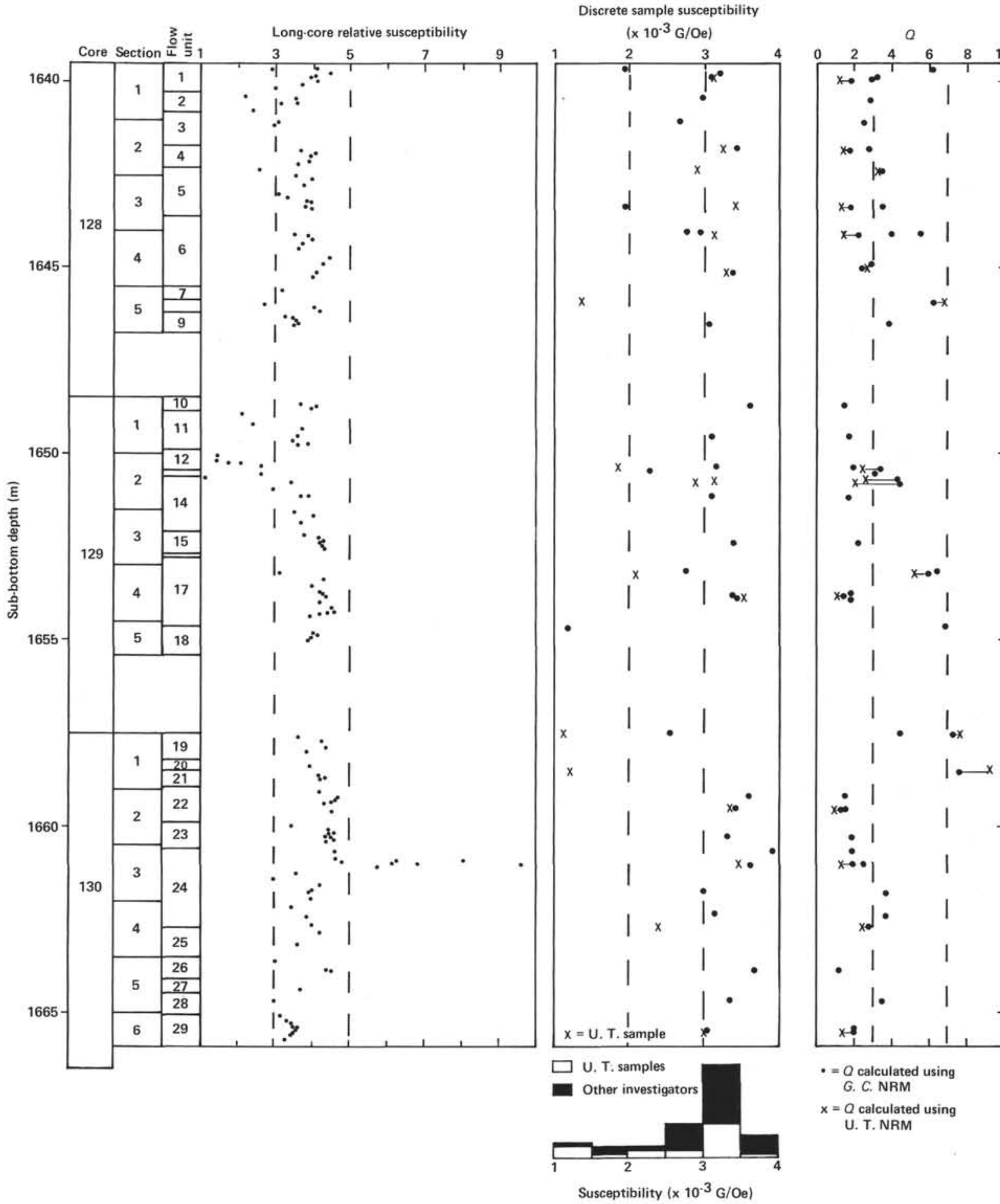

Figure 1. Long-core susceptibility, discrete sample susceptibility, and Konigsberger ratio (Q) of basalts from Hole 534A. (In the plot of Q, the lines connecting • to × show how Q changes when land-based NRM intensities are used in place of shipboard intensities; U.T. = University of Texas; *G.C.* = *Glomar Challenger*.)

and one set of these was studied at the University of Texas (U.T.) laboratory. The remaining samples were used for paleomagnetic investigations by Ogg and Steiner, and their results are reported separately in this volume.

The 18 samples were stored in a magnetically shielded room (~ 100γ) for approximately 2 months prior to remeasurement of their NRM, 4 months after the initial measurement. The intensities and inclinations are compared with the shipboard measurements in Table 1. The differences between the two readings can be attributed to two causes: (1) a calibration offset between the shipboard Digico and the U.T. cryogenic magnetometers, which may explain some intensity differences; and (2)

Table 1. Comparison of shipboard and land-based measurements of NRM intensity and inclination and initial susceptibility (χ) and Konigsberger ratio (Q), Hole 534A.

Sample (core-section, cm from top of section)	Sub-bottom depth (m)	NRM intensity ($\times 10^{-3}$ emu)			NRM inclination			χ[e]	Q[f]
		G.C.[a]	U.T.[b]	Δ(%/100)	G.C.	U.T.	Δ(°)		
128-1, 46	1639.96	33.9	22.0	−0.35	19.9	15.0	−4.9	3.15	1.18
128-2, 86	1641.86	32.3	26.5	−0.18	46.0	44.5	−1.5	3.26	1.38
128-2, 138	1642.38	59.9	29.5[c]	−0.02	48.9	49.4	+0.5	2.92	3.42
128-3, 87	1643.37	37.5	28.0	−0.25	39.0	35.4	−3.6	3.47	1.37
128-4, 15	1644.15	39.0	9.3[d]	−0.28	28.2	35.1	+6.9	3.16	1.49
128-4, 112	1645.12	54.4	56.1	+0.03	31.9	30.4	−1.5	3.30	2.88
128-5, 45	1645.95	50.1	18.5[d]	+0.11	23.2	26.7	+3.5	1.36	6.94
129-2, 40	1650.40	36.5	28.0	−0.23	20.5	17.4	−3.1	1.86	2.56
129-2, 72	1650.72	80.0	16.4[d]	−0.39	23.1	25.3	+2.2	3.13	2.67
129-2, 75	1650.75	77.3	36.2	−0.53	22.8	34.1	+11.3	2.90	2.12
129-4, 23	1653.23	72.0	31.9[c]	−0.11	33.9	37.5	+3.6	2.07	5.22
129-4, 86	1653.86	30.5	25.4	−0.17	42.8	44.8	+2.0	3.55	1.21
130-1, 5	1657.55	40.7	43.3	+0.06	19.5	18.7	−0.8	1.13	7.83
130-1, 106	1658.86	55.3	27.6[c]	0.00	33.8	33.6	−0.2	1.21	9.25
130-2, 56	1659.56	24.0	19.9	−0.17	59.8	53.0	−6.8	3.36	1.01
130-3, 55	1661.05	38.4	28.4	−0.26	37.4	33.6	−3.8	3.48	1.39
130-4, 78	1662.78	39.0	17.8[c]	−0.09	36.6	32.2	−4.3	2.42	2.50
130-6, 54	1665.54	35.2	24.1	−0.32	17.8	18.5	+0.7	3.01	1.36

[a] *G.C.*: measured on Digico magnetometer aboard *Glomar Challenger*.
[b] U.T.: measured on cryogenic magnetometer at University of Texas.
[c] Half sample; intensity should be approximately half of *G.C.* intensity.
[d] Small half sample; intensity should be approximately one-third of *G.C.* intensity.
[e] Initial susceptibility, $\times 10^{-3}$ G/Oe.
[f] Königsberger ratio calculated using U.T. NRM intensities. $H = 0.491$ Oe.

acquisition or decay of viscous components of magnetization between the two sets of measurements. The Königsberger ratio (Q) of these samples is very low; over 70% have values between 1 and 3 (Table 1 and Fig. 1). Such a low Q is often observed in basalts that can acquire a significant component of viscous magnetization. This tendency was examined for 10 1-in. samples in a preliminary study of time-dependent magnetization.

TIME-DEPENDENT MAGNETIZATION

After NRMs were remeasured, the samples were placed in a 1-Oe field, produced by a coil located inside a large μ-metal cylinder. In all cases, the field was applied along the axis of the cylindrical specimen. After one week of acquisition, the decay of induced magnetization in a field-free environment was measured with a cryogenic magnetometer interfaced with a computer. Measurements of the axial component were recorded continuously, beginning about 15 s after removal from the field and continuing for several hours. The sample then remained in a zero magnetic field ($< 5\gamma$), and two additional decay measurements were taken at intervals several days apart. Table 2 details the experimental sequence and presents the results as relative intensities with respect to the NRMs measured in the laboratory.

All 10 samples exhibit a viscous magnetization, which, for most samples, consists of two components, a Richter aftereffect and a simple log t decay (Fig. 2). Richter

Table 2. Relative intensity of axial component of magnetization for 10 samples subjected to the viscosity experiment described in the text, Hole 534A.

Sample (core-section, cm from top of section)	NRM G.C.	$\Delta\tau_0$ (month)	NRM U.T.	$\Delta\tau_1$ (day)	VRM	$\Delta\tau_2$ (min.)	Decay 1	$\Delta\tau_3$ (day)	Decay 2	$\Delta\tau_4$ (day)	Decay 3
128-1, 46		4	−18.66[a]	7.9		100		2.7		5.9	
	1.54		1.00		1.08		0.93		0.90		0.85
128-3, 87		4	2.42	7.6		900		2.0		5.9	
	1.68		1.00		−1.23		0.03		0.44		0.47
128-4, 112		4	41.83	8.0		39		2.7		5.9	
	0.98		1.00		0.96		0.97		0.97		0.95
129-2, 40		4	−24.54	7.6		280		2.8		6.0	
	1.33		1.00		1.11		1.00		1.03		1.00
129-2, 75		4	13.62	7.6		162		2.7		5.9	
	1.70		1.00		0.62		0.71		0.85		0.79
129-4, 86		4	14.40	7.2		560		2.6		6.4	
	1.36		1.00		0.71		0.90		0.98		0.95
130-1, 5		4	5.11	7.1		52		3.0		6.5	
	0.65		1.00		0.79		0.89		0.90		0.95
130-2, 56		4	7.62	6.8		72		3.0		6.8	
	1.02		1.00		0.57		0.84		0.93		0.91
130-3, 55		4	−23.51	7.0		77		2.9		6.7	
	1.29		1.00		1.18		1.04		1.00		0.94
130-6, 54		4	−19.95	6.9		150		2.9		6.7	
	1.43		1.00		1.08		0.93		0.91		0.81

Note: For each sample, the top line lists the time between measurements and the NRM intensity of the axial component before the sample was placed in a 1-Oe field. The bottom line lists all measurements relative to this intensity.
[a] Intensity of axial component $\times 10^{-3}$ emu.

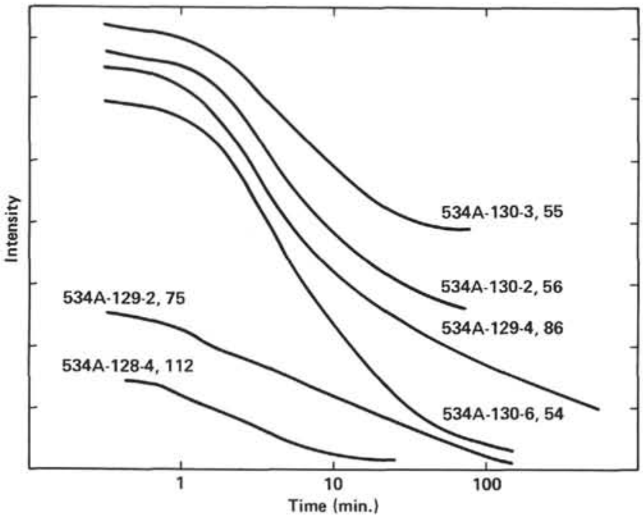

Figure 2. Change in intensity of axial component upon removal from 1-Oe field after 1 week of exposure. (Vertical intervals in plot are 0.5×10^{-3} emu for all samples except Sample 534A-130-3, 55 cm, in which case intervals are 1.0×10^{-3} emu.)

aftereffect (e.g., Chikazumi, 1964; Dunlop, 1973a) is observed if a sample contains magnetic grains whose relaxation times are limited to a range between $\tau_1 < t < \tau_2$ when τ_1 and τ_2 lie within the range of experimental times (Fig. 3A). The VRM of lunar samples is well explained by this effect, except that the lower end of the relaxation time distribution is shorter than could be measured (Gose and Carnes, 1973; Carnes et al., 1975). A VRM that is linear with log t results from a relaxation time distribution whose limits exceed the duration of the experiment (Fig. 3B) and is generally attributed to wall

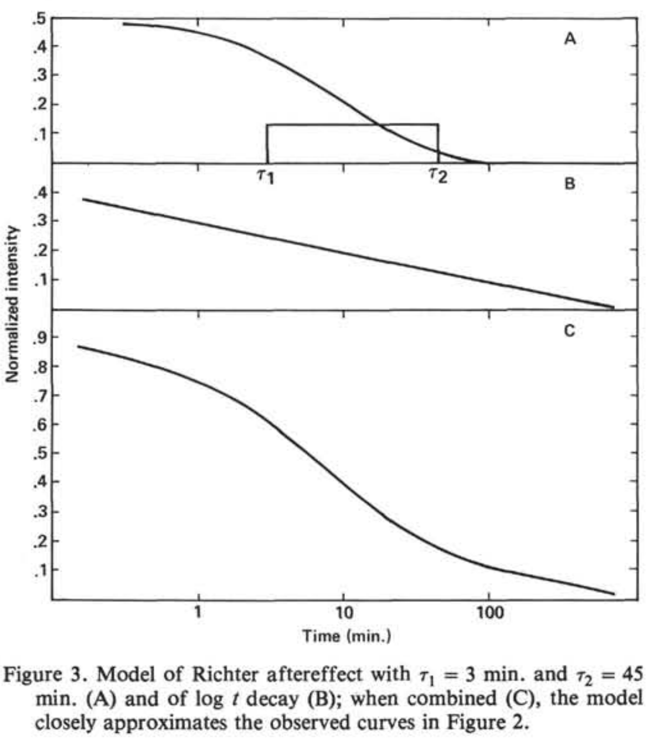

Figure 3. Model of Richter aftereffect with $\tau_1 = 3$ min. and $\tau_2 = 45$ min. (A) and of log t decay (B); when combined (C), the model closely approximates the observed curves in Figure 2.

motion in multidomain grains, but can also result from single domain grains with a very broad relaxation time spectrum. The sum of these two effects (Fig. 3C) closely matches the observed data (Fig. 2).

It is quite straightforward to calculate the two limits of the relaxation time distribution for the observed Richter effect (see Chikazumi, 1964). For these basalts, the effect is the result of relaxation times between about 100 and 3000 s. In order to calculate the corresponding grain size, one needs to know the coercive force and saturation magnetization of the sample. These have not yet been determined through A.F. demagnetization and hysteresis loops, because such techniques can affect the ability of the sample to acquire a VRM (Lowrie and Kent, 1978). However, the grain size does not depend very strongly on the choice of parameters, and the observed values for τ_1 and τ_2 always imply a very narrow range of grain sizes (Table 3).

DISCUSSION

The results of these experiments confirm previous studies that demonstrated that almost all oceanic basalts readily acquire a viscous remanent magnetization (Lowrie and Kent, 1978). Also in agreement with previous data is the observation that the VRM acquired in a 1-Oe field can amount to a significant percentage of the stable remanent magnetization. This percentage can be quite variable, however, ranging from a few percent to more than 100 percent of the stable remanent magnetization. Because this VRM can be acquired within minutes and because the magnetic field inside the paleomagnetic facility aboard the *Glomar Challenger* is about 1 Oe, it is questionable how meaningful shipboard measurements are.

The surprising finding of this experiment is the occurrence of two grain populations that give rise to two distinct time-dependent magnetizations. The log t dependence of magnetization is frequently observed in oceanic basalts and can be due to domain wall motion in multidomain grains or to the presence of single domain grains with a very broad relaxation time spectrum.

Superposed on the log t decay is a Richter aftereffect that is caused by grains in an extremely narrow size range ($\Delta d \simeq 20$ Å). Depending on the values of the coercive force and saturation magnetization, the absolute grain size will change, but the range of sizes remains narrow. It is suggestive of equidimensional magnetite particles because they have a very narrow single domain range at about 400Å (Dunlop, 1973b). However, two

Table 3. Calculated grain diameters (d) for different values of relaxation time (τ), coercive force (H_c), and saturation magnetization (J_s).

	H_c (Oe)	J_s (emu/cm^3)	τ_1 (s)	τ_2 (s)	d_1 (Å)	d_2 (Å)	Δd (Å)
Magnetite	100	478	100	2000	434	451	17
Magnetite	100	478	180	2700	438	452	14
Ti-magnetite	100	100	180	2700	737	762	25

Note: Diameters are calculated under the assumption that the particles are spherical. Note the small Δd in all cases.

observations cast doubt on this interpretation. If the samples contain single domain particles, one would expect that they should also have superparamagnetic grains. If that were true, the lower relaxation time τ_1 should be shorter than our experiment can measure, and the initial roll-off should not have been observed. In addition, the upper limit of activated relaxation times τ_2 for single domain grains is a function of length of time, t_A, for which the magnetic field was applied, that is, $\tau_2 = 1.78t_A$ (Gose and Carnes, 1973). We had applied the field for about 1 week yet observed a τ_2 of only 1 hr., which suggests that these were not single domain grains.

At this point we do not have a satisfactory explanation of why the samples exhibit a Richter aftereffect. We offer the following speculation concerning τ_2. As a SD (single domain) particle grows, its relaxation time increases. For equidimensional magnetite grains, it is quite possible that the grains become multidomain before their relaxation time reaches values in excess of the experimental time, resulting in a τ_2 value that is independent of the field exposure time for application times larger than some small τ_2. Clearly, extensive additional experiments, particularly at low temperatures, are needed before we can hope to explain the Richter effect in these and other oceanic basalt samples.

CONCLUSION

As the low Königsberger ratio suggested, these samples can readily acquire a VRM. However, there is no simple correlation between Q and viscosity. Samples with $Q < 3$ acquired a VRM ranging from 4 to 223% of their NRM, and the only sample with $Q > 3$ acquired a VRM equal to 20% of its NRM. The presence of a VRM implies that the reported Q values are maximum values. This is because the susceptibility, and hence Q, were measured by applying a magnetic field for a very short time, typically a few seconds. The induced magnetization would have increased with measuring time as the VRM component grew, and the Königsberger ratio would have decreased, had the measuring interval been longer.

It is therefore necessary to question the validity of using laboratory measurements of susceptibility and Q for assessing the relative importance of the stable and induced magnetization in the interpretation of magnetic anomalies. Because the samples have been exposed *in situ* to the geomagnetic field for very long times, the induced magnetization will be underestimated in short-term laboratory measurements of these basalts and others with similar magnetic viscosity.

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